



Early Journal Content on JSTOR, Free to Anyone in the World

This article is one of nearly 500,000 scholarly works digitized and made freely available to everyone in the world by JSTOR.

Known as the Early Journal Content, this set of works include research articles, news, letters, and other writings published in more than 200 of the oldest leading academic journals. The works date from the mid-seventeenth to the early twentieth centuries.

We encourage people to read and share the Early Journal Content openly and to tell others that this resource exists. People may post this content online or redistribute in any way for non-commercial purposes.

Read more about Early Journal Content at <http://about.jstor.org/participate-jstor/individuals/early-journal-content>.

JSTOR is a digital library of academic journals, books, and primary source objects. JSTOR helps people discover, use, and build upon a wide range of content through a powerful research and teaching platform, and preserves this content for future generations. JSTOR is part of ITHAKA, a not-for-profit organization that also includes Ithaka S+R and Portico. For more information about JSTOR, please contact support@jstor.org.

THE
JOURNAL OF GEOLOGY

JULY-AUGUST 1918

CORAL REEFS AND SUBMARINE BANKS

W. M. DAVIS
Cambridge, Massachusetts

PART III

Submarine banks in the coral seas.—Most modern writers on the coral-reef problem have followed Darwin in explaining the submarine banks of the coral seas as submerged atolls which had subsided so fast that their reefs were not built up to the sea surface; but they are regarded by Daly as representing still-standing preglacial volcanic islands, reduced first by long-continued erosion to low relief, and then by abrasion before or during the glacial period to smooth platforms, around which postglacial reefs have been less completely formed than around the corresponding platforms of ordinary atolls. Thus here again subsidence is the essential factor of the older explanation, while it is essentially excluded from the newer one. One explanation is as easily conceived as the other; the difficult matter is, as before, to find appropriate tests by which the true explanation can be determined. If the submarine banks were today all of the same depth and if they still preserved the form of very flat cones which abrasion would give them the problem might be easily solved; but their depths vary and their form is not that of flat cones but, as a rule, of shallow saucers; thus the problem

becomes complicated. The dimensions of some of the largest banks in nautical miles and fathoms are as follows:

Bank	Location	Length	Breadth	Central Depth
Macclesfield	China Sea	95	35	55-60
Tizard	" "	25	10	48
Seychelles	Indian Ocean	200	80	40
Great Chagos	" "	90	70	48
Amirante	" "	90	20	30
Namuka	Pacific Ocean	30	25	45

The Macclesfield bank, the largest of several submarine banks in the China Sea, is a good example. Interesting accounts of it have been published by the British Admiralty.¹ It possesses an incomplete rim, occupied by living corals, which rises around the margin to minimum depths of about 10 fathoms. Now if this bank has an abraded platform for a foundation, the depth of the platform should increase from the center outward and should be at least 10 or 15 fathoms more at the margin than at the center. Hence the bank margin, originally 55 or 60 fathoms and now only 10 fathoms below present sea-level, must have been built up at least 45 or 50 fathoms in postglacial time, and at half-distance from margin to center the bank must have been aggraded 15 or 20 fathoms in order to convert its initial flat cone into the present shallow saucer. But if so much change has taken place outside of the center, the center itself must have been significantly aggraded, and its actual depth is therefore not a true measure of the depth of its buried rock foundation.

The same uncertainty prevails as to the depth, not to say the very existence, of the supposed rock platforms that are assumed to serve as foundations for other submarine banks. The Great Chagos bank of the Southern Indian Ocean, taken by Darwin as the type of a drowned atoll, measures 90 by 70 miles; it has a broad, flat floor, 48 fathoms in depth near the center, and a broad rim at an average depth of 16 fathoms, from which a narrower rim rises nearer to the surface. The Amirante bank, in the same

¹ W. U. Moore and P. W. Bassett-Smith, *China Sea Tizard, and Macclesfield Banks*, Hydrog. Dept., Admiralty, London, 1889. P. W. Bassett-Smith, *Dredgings Obtained on the Macclesfield Bank*, *Ibid.*, 1894.

ocean, north of Madagascar, measures 90 by 20 miles, with a central depth of 30 fathoms and a rim generally under 10 or 20 fathoms of water, bearing living coral and emerging in 21 low coral islands. Even more extraordinary is the vast Seychelles bank, east of the Amirante bank, the largest example of its kind; as represented on Admiralty chart 721, it measures about 200 by 80 miles; its general depth varies from 25 to 35 fathoms, with a maximum of 40 fathoms not far from the central island, Mahé, and with a shoal margin on the northeast where several reefs and coral-sand islands reach the surface. Here, as in the Macclesfield bank, the marginal depth of an abraded platform should be significantly greater than its center, and the present central depth of the bank is no safe measure of the depth of a platform beneath it. The central island, Mahé, represented in more detail on Admiralty chart 1072, is singular in being composed of non-volcanic, granitic rocks; it measures 17 by 4 miles, and its highest summit rises 2,993 feet above sea-level; its shore line is not clift, but beautifully embayed, with the bayheads occupied by delta plains and the dividing spurs trailing away in declining points with no cliffs at their ends.¹ Discontinuous fringing reefs border the points. Several other smaller granitic islands rise not far away.

Mahé has, moreover, not only a narrow fringing reef at present sea-level, but also at a height of 80 feet patches of an elevated fringing reef,² which must, like the sea-level fringe, lie unconformably on the granitic slopes of the island; the date of the elevated reef with respect to the date of origin of the great submarine bank has not been studied by any of the visitors to the island—Pelly, Wright, Coppinger, Keller, Chun, Gardiner—whose accounts I have read; but if the elevated reef be the older of the two, it ought to have been completely worn away while the great bank, whatever its origin, was forming; and if the reef be the younger of the two, then while it was forming the great bank must have had a maximum

¹ Good views of the Mahé shoreline are given by C. Keller, *Die ostafrikanischen Inseln* (Berlin, 1898), p. 160; C. Chun, *Aus den Tiefen des Weltmeeres* (Jena, 1900), p. 432; and J. S. Gardiner, "The Indian Ocean," *Geogr. Jour.*, XXVIII (1906), 313-32, 454-65; see p. 457.

² C. Keller, *op. cit.*, p. 158; C. Chun, *op. cit.*, p. 426.

depth of over 50 fathoms, and the bank would then be even more difficult of explanation by the glacial-control theory than it is when considered without regard to the elevated reef. However, perhaps the elevated reef, if it really occurs, is only a remnant of a much larger ancient reef which was, after elevation, eroded to its present moderate dimensions while the great bank was forming; in this case it would cause no embarrassment, provided the formation of the bank would not require so long a time as to involve the complete removal of any pre-existent reef and the partial erosion of the granitic foundation as well. The study of Mahé by the zoölogists and oceanographers who have visited it has not included an attack on this problem.

The absence of spur-end cliffs on this granitic island discountenances the idea that it rises from an abraded platform; and to this it may be added that, not only the breadth of its bays, but also the strong unconformity between the sea-level fringing reefs and the granitic points which they adjoin, indicates a greater measure of erosion beneath present sea-level than could have been accomplished while the ocean was lowered during the glacial period; and this calls for subsidence from a former higher stand.

Namuka bank, the largest of several banks in the Tonga or Friendly islands of the South Pacific, is peculiar in having a slanting surface; it is 30 fathoms deep on the eastern side, where it is rimmed by a reef that rises toward or to the surface; it inclines gradually to the western, reefless margin, where its depth varies from 50 to 70 fathoms. Hence this bank has probably been tilted since it was formed. Other banks in the Tonga group also suggest recent deformation; none of them confirm the assumption that their foundations have enjoyed a long-enduring stability.

As compared with the profound basins of the ocean, submarine banks may be all described together as having small and similar depths; but when separately examined their individual depths vary by large fractions of their mean depth. If large and small banks are compared their depths are in a general way found to decrease with their diameters, but there are many departures from this rough rule. The vast Seychelles bank (40 fathoms) is not so deep as the Great Chagos (48 fathoms) and the Macclesfield (55-60

fathoms) banks; the smaller banks are usually 25 fathoms deep, but the smallest are about as deep as the middle-sized banks: thus Turpie bank, 23 miles long, is 27 fathoms deep; for Alexa bank the figures are 18 and 24; Waterwitch, $10\frac{1}{2}$ and 25; Penguin, 9 and 25; Hazel Holme, 5 and 25. The Saya de Malha bank in the Southern Indian Ocean southeast of the Seychelles bank is most exceptional in this respect; although only about 20 miles in diameter it has a central depth of 64 fathoms, with a rim of 20 fathoms or less around the northeastern margin. I have not been able to conceive of any way to account for this bank under the postulates of the glacial-control theory.

As to banks of moderate size and of 20 or 25 fathoms depth, any platform that lies beneath them should be as deep as, indeed somewhat deeper than, the platforms of the great banks; hence the thickness of the deposits by which the smaller banks are aggraded must measure at least 20 or 30 fathoms; but as this measure is obtained only by assuming that the platform exists at a proper depth, it has no particular value.

It is interesting to note in passing that the central areas of the smaller reef-rimmed banks have extraordinarily smooth floors, presumably the work of the heavy swell that must sweep across their submerged rims and distribute very evenly all available sediments. It was, indeed, the smooth floors of these banks that led Wharton to abandon Darwin's theory of subsidence, which he conceived as requiring a "deeply concave surface" in the floors of atolls, whether their rims be at sea-level or below; he suggested instead that the flat floors of atoll lagoons and of submarine banks represented former volcanic islands, smoothly truncated by the waves of the ocean at its present level,¹ and he tacitly postulated that reef-building corals were not present until the work of abrasion was completed. Daly gives a more reasonable statement of the conditions under which abrasion could act, but in saying, "Wharton's choice of the agency which produced the flatness of lagoon floors and of banks seems irresistible," he does not make sufficient distinction between the evenly aggraded, reef-rimmed floors of the smaller submarine banks at such depths as 20 and 25 fathoms, and

¹ W. T. L. Wharton [Address], *Rep. Brit. Assoc. Adv. Sci.* (1894), pp. 699-710.

their supposed abraded platforms, which according to the glacial-control theory should be some 20 fathoms deeper; and in adding that Wharton "rightly regarded this flatness as fatal to the Darwin-Dana theory" (196), he disregards the capacity of lagoon waves in true atolls and of the ocean swell over submerged atolls or banks to produce smooth lagoon floors, whatever the form of the buried foundation. This capacity seems to me well proved. Hence, as far as the features of atolls and submarine banks are concerned, the necessity of accepting the glacial-control theory is not constraining; the possibility of accounting for the form and the depths of atoll-lagoon floors and of submarine banks as a result of their slow, variable, intermittent subsidence is still open.

Supposed abraded platforms beneath submarine banks.—The variations in the depths of atoll-lagoon floors and of submarine banks, although of considerable measure, are, with the exception of the Saya de Malha bank, by no means so great as to be altogether incompatible with the existence of abraded platforms at uniform depths beneath them, as required by the glacial-control theory; but they seem to me too great to demonstrate the correctness of that theory to the exclusion of all others. On the contrary, they throw a certain amount of doubt upon the theory by the necessity that they impose of making a number of unproved, perhaps unprovable, assumptions in order to bring about a sufficient agreement among various unlike quantities. This doubt may be solved arithmetically by saying: "Since probably not more than 5 to 25 m. can be allowed for the thickness of the post-glacial calcareous veneer in the wider lagoons, the accordance of platform depths for the wider lagoons and reefless banks seems clear. . . . The agreement is visible in spite of possible, though necessarily slight, uplift or subsidence" (Daly, 193, 194); but such a solution is not convincing. It involves the venturesome postulate of a long-enduring still-stand of the islands concerned, the very questionable process of abrasion while the reefs were supposedly dead, and the entirely unknown total thickness of calcareous deposits in lagoons and on banks. A solution containing so many undetermined quantities must remain very uncertain. The uncertainty will be more apparent if we return to the case of the

Macclesfield bank, which is instanced as typical of its class, and inquire particularly as to the validity of the assumptions that are necessary in order to explain it by the glacial-control processes. The assumptions appear to be about as follows:

If a volcanic island about the size of Hawaii stood still long enough in preglacial time, it would be reduced to low relief and would be surrounded by shoals of its own detritus mingled with reef deposits. If any defending reefs were killed by the chilled and lowered glacial ocean, the low island would be attacked by the waves; and, if the attack endured long enough, the island, still stationary, would be reduced to a smooth platform having the form of a very flat cone. Such a platform would have about the area of the Macclesfield bank. Then as the sea finally warmed and rose again the bank would be more or less rimmed with a reef and aggraded with wave-swept sediments. This succession of suppositions is, like many another, easily conceivable; but it is so full of improbabilities that it cannot command acceptance, as the following considerations will show.

The instability of the Australasian Archipelago.—The improbability that wave attack was effective in truncating preglacial islands has already been sufficiently set forth; some uncertainty as to the lowering of the glacial ocean by so much as 35 or 40 fathoms will be pointed out below in the section on extra-tropical submarine banks; we may here inquire whether the region of the Macclesfield bank can be fairly regarded as one of long-enduring stability. No inquiry based on geological evidence regarding the region concerned appears to have been made on this point. Stability seems to have been assumed in order that an even platform might be abraded and a smooth bank formed by subsequent aggradation. If this assumption be temporarily set aside, the geological relations of the bank may be inquired into impartially. The general situation of the bank in a deep sea on the border of a large continent is not one that would be chosen, on general principles, as presumably stable. The prevailing opinion as to the instability of continental borders is summarized by Chamberlin and Salisbury, who suggest that mutual crowding and crumpling may take place, accompanied by fracture and slipping, where the edges of elevated continental

segments and of depressed oceanic segments of earth's crust adjoin; and that tracts of low resistance to deformation may be expected at or near the border of continents, "where the crust is already flexed in its descent from the continental platforms to the ocean bottoms."¹

Furthermore the China Sea, from the depths of which the Macclesfield bank rises, is bordered by embayed coasts on nearly all sides. The embayments of the coast of China in the Hong Kong district are manifestly due to the submergence of a maturely eroded mountainous area; the reef-free headland points are little clift, and the breadth as well as the probable rock-bottom depth of the bays appears to be greater than could have been produced by subaërial erosion during the glacial epochs of the glacial period; thus recent subsidence is indicated on that side of the China Sea. On the east the sea is inclosed by the Philippine Islands, where diverse earth movements of modern geological dates are abundantly proved. The southern part of the sea, where Tizard and other submarine banks rise, is inclosed on the east by the long island of Palawan, the southernmost member of the Philippine group, with a wonderfully embayed coast, as shown on Admiralty chart 967, or better on United States Coast Survey chart 4316; its headlands are not clift and are almost free from fringing reefs; they have a rapid descent to depths of from 15 to 25 fathoms close to the shore line. The chart has every appearance of accuracy; hence the absence of cliffs on the delicate spur-end points between the intricate embayments is significant. A submarine bank stretches westward from the embayed shore line; it is from 15 to 30 miles wide and from 40 to 60 fathoms deep near its outer margin, where it is rimmed by an imperfect barrier reef that rises discontinuously toward the sea surface. It seems impossible to regard this broad bank as the work of abrasion, because the headlands of the coast behind it are not clift; it seems equally impossible to regard the broad embayments of the coast as the product of subaërial erosion during the epochs of lowered sea-level in the glacial period, because of their great width; recent and rapid subsidence of a reef-fronted coast is thus strongly indicated. Farther north the west coast of Luzon is much less embayed than Palawan and is without a broad off-shore bank;

¹ *Geology*, I (1904), 522; II (1904), 127.

here, according to Becker, elevation has predominated in late Tertiary and post-Tertiary time; thus differential movements of Palawan and Luzon are suggested. Other differential movements of late date within the Philippines are abundantly proved by various records, such, for example, as the elevated reef terraces briefly described by Becker as occurring on the islands of Cebú and Negros (see below) but absent on neighboring islands. Evidence of recent and rapid subsidence in some of the Philippine Islands, as shown by their narrow, unconformable fringing reefs, will be presented in a forthcoming article in the *Bulletin of the Geological Society of America*.

But besides all this it must be remembered that the China Sea is, unlike the shallow Yellow Sea on the north and the shallow Java Sea on the south, one of those deep mediterraneans that are inclosed along the eastern border of Asia by festoons of islands in which, geologically, modern movements are the rule. Darwin wrote of this region, "Between the Indian and Pacific oceans . . . north of Australia, lies the most broken land on the globe, and there the rising parts are surrounded and penetrated by areas of subsidence" (143). He had little evidence on which to base his statement, but he was right. Molengraaff much later characterized the same region as follows:

In the eastern part of the archipelago (between Borneo and Australia) where a complicated topography of the land and the sea bottom prevails, deep-sea basins have been formed by subsidence [in the "latest geological periods"], and, during the same time, ranges of islands have been raised above the sea, caused by antagonistic movements which are probably still in progress.¹

The same writer cites from the report of the Dutch "Siboga" expedition a remarkable dredging record made on September 1, 1900, for the middle of the Ceram Sea, between Celebes and New Guinea:

From a depth ranging from 1,633 to 1,304 m. over a distance of no less than three nautical miles, large quantities of recent, reef-building coral were there dredged, which . . . by a thick cover of manganese revealed their long stay in the sea-water. . . . The nearest point in these regions where living reef-building corals occur near the surface lies at 42 kilometers from the point where the dredging took place. . . . In order to explain the result of this dredging

¹ G. A. F. Molengraaff, "On Recent Crustal Movements in the Island of Timor," *Proc. k. Akad. Wet. Amsterdam*, XV (1913), 224-35.

I should rather suppose that on that spot in the Ceram Sea . . . a drowned coral island rises to about 1,300 m. below sea-level. Such a supposition seems justified if it is borne in mind that the Ceram Sea is one of the most remarkable trough-shaped deep basins in the eastern part of the Indian archipelago, the origin of which is probably connected with crust movements in Pleistocene and post-Pleistocene times. They were formed by downward movements, simultaneous with, and more or less compensated by, elevations of about equal amount of other parts.¹

The crustal instability inferred for the Ceram Sea is not exceptional. Recent studies in other parts of the great archipelago attest a wide extension of diverse movements in late geological times. Thus the Sarasin brothers infer various movements of Celebes in modern geological periods,² and more detailed studies of the same island by Ahlburg and Abendanon reach similar conclusions. The first of these two investigators has published a monograph in which various changes of island level are described.³ The second has given an abstract of his report on a geological and geographical traverse of middle Celebes in the *Journal of the Dutch Geographical Society*; it is there stated that a region of crystalline rocks which was reduced to a peneplain in Oligocene time has suffered great displacements in later periods, including plio-Pleistocene upheavals of 1,000 meters, and subsidences of similar measure; the deepening of the adjoining seas is explicitly stated to have accompanied the elevation of land areas, thus indicating strong differential movements.⁴ Many other articles might be cited to the same conclusion. Thus Becker⁵ and Smith⁶ both testify to diverse movements in the

¹ G. A. F. Molengraaff, "The Coral-Reef Problem and Isostasy," *Proc. k. Akad. Wet. Amsterdam*, XIX (1916), 610-27; see p. 624. Fine charts of the Australasian mediterraneans are given by G. F. Tyddeman, *Hydrographic Results of the Siboga Expedition*, Leiden, 1903.

² P. and F. Sarasin, *Ueber die geologische Geschichte . . . der Insel Celebes*, Wiesbaden, 1901.

³ J. Ahlburg, "Versuch einer geol. Darstellung der Insel Celebes," *Geol. and Pal. Abh.*, XII (1913), heft 1.

⁴ E. C. Abendanon, "Historische Geologie van Midden-Celebes," *Tydschr. k. ned. Aardr. Gen.*, XXIV (1917), ?-456, 548-64.

⁵ G. F. Becker, "Report on the Geology of the Philippine Islands," *U.S. Geol. Surv.*, 21st Ann. Rept., 1901, Part III, pp. 1-139; see pp. 19, 69.

⁶ W. D. Smith, "Contributions to the Physiography of the Philippine Islands. I, Cebú Island," *Phil. Jour. Sci.*, I (1906), 1043-57.

Philippines: Becker states that there is a great unconformity on Cebú and Negros between the Miocene lignitic series and the coral-limestone mantle, which in Cebú extends to an altitude of 2,362 feet; Smith gives an account of the island of Cebú, the strata of which have suffered profound folding and much erosion followed by submergence, reef formation, and emergence.

Instability of this region is also to be inferred from the mention of disturbed Tertiary deposits in Kotô's account of the Malayan Archipelago,¹ and in Richthofen's essay on "Formosa and the Riukiu Islands."²

In view of the accordant testimony of all these observers it would seem that the deep mediterraneans on the eastern border of Asia have presumably suffered deformation in modern geological time, and that long-enduring instability is by no means a probable characteristic of the Macclesfield bank. Indeed, as Suess³ and others have suggested, the deepest seas are, like the highest mountains, very likely due to modern deformation. If one were asked to select a deep-sea area where rapid subsidence might be expected and where drowned atolls might therefore occur, and where long-continued stability appears improbable, the China Sea would seem to be about as good an example as any other. The Central Pacific has probably suffered much less deformation of recent date than the China Sea and its neighbors; and yet there are signs of subsidence even in the Central Pacific, as was pointed out in the accounts of Hawaii and Tahiti, previously given.

Subsidence or stability in the Indian Ocean.—As to the great submarine banks of the Indian Ocean, they are so remote from continents and large islands of decipherable history that speculation regarding their origin is not narrowly limited. Little help toward reaching a sound conclusion concerning them is found in the published opinions about the small islands of the Indian Ocean. For example, C. W. Andrews (not to be confounded with E. C. Andrews,

¹ B. Kotô, "On the Geologic Structure of the Malayan Archipelago," *Jour. Coll. Sci. Tokyo*, XI (1899), 83-119.

² F. V. Richthofen, "Geomorph. Studien aus Ostasien: III, Die morphol. Stellung von Formosa und den Riukiu Inseln," *Sitzungsber. Akad. Wiss. Berlin*, 1902.

³ E. Suess, *Das Antlitz der Erde*, III (1909), 336.

of Sydney, New South Wales), who was sent from England to study Christmas Island, an elevated atoll nearly 1,200 feet high in the eastern part of the Indian Ocean, seems to have followed the belief announced by Suess regarding the elevated Loyalty atolls of the Western Pacific; for, although he recognized that the basal limestones of shallow-water deposition must have been depressed in order to be covered by hundreds of feet of later limestones, he afterward suggested that the altitude of Christmas Island might not be due so much to a local uplift of 1,200 feet from an ocean of stationary level as to a subsidence of the ocean by 1,200 feet while the island stood still;¹ he thus, perhaps unintentionally, implied that all the ocean bottom elsewhere recently subsided 1,200 feet, and that all the islands and all the continents which did not emerge at the same time by the same amount also subsided with the ocean; or else that a smaller part of the ocean bottom subsided by a proportionately greater amount. If we could follow this author's lead we should not hesitate to explain the submarine banks of the Indian Ocean by subsidence, for a hypothesis which accounts for the local emergence of a small island by a great and widespread sinking of the ocean bottom elsewhere need not shrink from explaining submarine banks by a subsidence of 40 to 50 fathoms. But for my own part I can find little support for the subsidence theory of coral reefs in a hypothesis so reckless as that which accounts for the emergence of Christmas Island by a sinking of most of the rest of the world; hence we must look elsewhere for evidence as to the behavior of the Indian Ocean bottom.

We thus come to Gardiner's study of the Maldivé atolls which led him to reject recent subsidence; for, although he accepts the depression of a large land area between India and Madagascar in Tertiary time, he asserts that "this depression is not the same as the slow and long-continued subsidence postulated by the upholders of Darwin's theory," and then, "seeing the absolute impossibility of subsidence affording any explanation" for the Maldives, he concludes that "an almost flat plateau at a depth of 140 to 170 fathoms was at one time formed by the erosion and denudation of

¹ C. W. Andrews, *A Monograph of Christmas Island (Indian Ocean)* (London, 1900), p. 298.

an original [still-standing] land mass, or more probably series of masses," and that the present shoals and reefs were afterward built up from the plateau to the sea surface.¹ He thus assumes, as Wharton did in his abrasion theory of atolls, that destructive processes first wore down a non-subsiding land mass or series of masses to a certain depth—in the case of the Maldives to the considerable depth of 150 fathoms—and that organic agencies, which must have been in abeyance while the down-wearing was in progress, then proceeded to overcome the destructive processes and to build up the present shoals and reefs. A hypothesis which accounts for the Maldives by upgrowth on a series of worn down, still-standing land masses might also explain a number of large submarine banks, imperfectly reef-rimmed, as still-standing masses that have been similarly worn down and are not yet completely built up again; but neither the postulates nor the processes of this hypothesis commend it.

Between the two extremes thus instanced Darwin's theory of reef upgrowth during intermittent subsidence seems to me a happy mean. Darwin applied his theory to the Maldives in a manner that is still consistent with the best interpretations of oceanographic problems; he regarded those numerous atolls in linear arrangement as resulting from the dissection of a great barrier reef upgrowing from a slowly subsiding foundation

of nearly the same dimensions with that of New Caledonia . . . for if, in imagination, we complete the subsidence of that great island, we might anticipate from the present broken condition of the northern portion of the reef . . . that the barrier reef, after repeated subsidences, would become during its upward growth separated into distinct portions; and these portions would tend to assume an atoll-like structure, from the coral growing with vigour round their entire circumferences, when freely exposed to an open sea [110].

Similarly Darwin's explanation of submarine banks by subsidence is more in accordance with all pertinent facts than is any explanation which involves their long-enduring stability. Whether the failure of reefs to grow up from such banks to the surface again is due to rapid subsidence, as Darwin thought, or to the injurious

¹ J. S. Gardiner, "The Origin of Coral Reefs," *Amer. Jour. Sci.*, XVI (1903), 203-13; see pp. 205, 206.

effects of "clouds of sediments" (211), as Daly suggests, this cause of failure being evidently as applicable to a drowned atoll as to an abraded platform, is a good subject for future investigation.

It is not only in general, but also in certain details that the theory of subsidence applies to the reefs of the Indian Ocean. Gardiner notes that "a most important point of difference in the Maldives from north to south lies in the gradual increase of the banks [lagoon floors] in depth," but as recent subsidence is to him an "absolute impossibility" he finds no satisfactory explanation for the increase. The large-scale Admiralty charts of the Maldives show the northern lagoons to be from 20 to 25 fathoms deep, and the southern ones from 40 to 45 fathoms, the change being accomplished in about 400 nautical miles. Darwin knew these facts and said in the first edition of his book, "I can assign no adequate cause for this difference in depth" ('42, 34), but he added in the second edition, "excepting that the southern part of the Archipelago has subsided to a greater degree or at a quicker rate than the northern part" ('74, 47). No one has since then offered any better explanation. It may be added that the Great Chagos bank lies about 300 miles south of the Maldives, and therefore Darwin's interpretation of it as a drowned atoll falls in very well with his explanation of the southward deepening of the Maldivian lagoons. When one recalls the various lines of geological evidence that point to the change of a large land area to a deep-sea bottom in the western part of the Indian Ocean, it seems as unreasonable to exclude recent subsidence from this region as to exclude it from the center of the China Sea.

Control of depth of submarine banks.—It is not only the flatness of submarine banks that has been regarded as beyond explanation by the subsidence theory; the accordance of their depths with respect to present sea-level has also been instanced as impossible of explanation by any other cause than prolonged abrasion of still-standing islands by the lowered glacial ocean. As to their origin by abrasion, suffice it to repeat the argument already stated, namely, if preglacial islands of almost any composition as broad as the larger submarine banks were completely truncated by the waves of the lowered glacial ocean, then the spur ends of maturely

dissected volcanic islands encircled by close-set barrier reefs ought today to be cut off in cliffs, the face of which, where not obscured by apposed deposits, should descend some tens of fathoms below present sea-level. This argument applies with special force if the great Seychelles bank be considered; for there the several granitic islands that are still visible strongly suggest that any large preglacial island occupying much of the area of the bank would have included a good proportion of resistant rocks in its constitution, and such an island could have been reduced to a platform of abrasion only by strong wave work continued long enough to cut spur-end cliffs on smaller volcanic islands elsewhere, around which narrow preglacial reefs were the only defense.

The inconsistency of the glacial-control theory in demanding broad abrasion for large atolls and submarine banks and in allowing only narrow abrasion around high volcanic islands within fringing or close-set barrier reefs is not, to my mind, satisfactorily explained by assuming that the atolls and banks were all represented in preglacial time by the deeply weathered, weak rocks of old, worn-down, still-standing islands, while the high islands were composed of resistant rocks of younger islands; for there is nothing to support such an assumption as to the preglacial representatives of atolls and banks except the consequence that is desired to follow from it; indeed the granitic islands of the Seychelles group contradict the assumption. Still less has a satisfactory explanation been offered for the other inconsistency—pointed out on page 294 in the account of Murea—of demanding that comparatively broad valleys must be eroded with respect to the lowered sea-level of the glacial period by the action of slow-working subaërial processes on the resistant rocks of high volcanic islands in the mid-Pacific area of assumed stability, and of denying that rock platforms and spur-end cliffs of significant dimensions can have been abraded in the same rocks while they were undefended by living reefs and attacked by the vigorous waves of the trade-wind seas during the same period of time as that in which the broad valleys were eroded. Nor can a satisfactory explanation of this inconsistency be found without concluding that the non-clift islands were protected all through the glacial period by living reefs. The upshot of this is that submarine

banks should not be regarded as the product of abrasion acting on still-standing reef-encircled preglacial islands while the ocean was lowered in the glacial period.

As to the depths of submarine banks being so accordant as to be beyond explanation, except as a consequence of abrasion at some such depth as 35 or 40 fathoms: It has already been pointed out that the actual depths are discordant, for they vary from 20 or 25 fathoms in the smaller banks north of Fiji to 40, 50, or 60 fathoms in the large banks of the China Sea and Indian Ocean, and to 64 fathoms in the exceptional Saya de Malha bank. Accordance is found only by subtracting larger measures of postglacial aggradation from the depth of the shallower banks and smaller measures from the depth of the larger banks; and even then the depth of the Saya de Malha bank is not brought into accord with that of its fellows. Daly has pointed out, as has been previously noted, that small banks are, on the average, shallower than large ones, and has explained this relation by showing that small banks should be more rapidly aggraded than large ones, in so far as the detritus is supplied from their rim; but according to this principle small atolls drowned by subsidence should also be more rapidly aggraded and therefore shallower than large ones: hence these variations of depth cannot serve as ground for valid choice between the two theories. As the depth of actual aggradation of submarine banks is absolutely unknown, measures of aggradation satisfactory to either theory may be freely assumed, but neither theory is thereby strengthened. Choice between them must be made on other grounds.

Possible balance of processes acting on submarine banks.— It is evidently conceivable that all the banks mentioned above may be neither drowned atolls built on subsiding foundations, nor ancient still-standing islands reduced to abraded platforms now more or less aggraded, but still-standing submarine masses of any origin now for the first time in process of building up toward sea-level, as postulated in the Rein-Murray theory of atolls. This conception cannot be proved or disproved by soundings; it can be tested only by indirect evidence, such as is afforded by the history of adjacent islands or continents and by the general action of organic

processes and of waves and currents. The history of adjacent islands indicates, as has already been shown, that long-enduring stability is not a necessary condition of the ocean floor in general, and that it is by no means a probable condition of the parts of the ocean floor where certain submarine banks occur. As to the accumulation of organic deposits on submarine banks, that is manifest enough; but the mere occurrence of such deposits does not prove that the banks are standing still instead of rising or sinking, or that loose deposits can aggrade a bank to small depths in the open ocean where heavy swell frequently sweeps over it. The submarine banks described by Buchanan¹ and Murray² may or may not exemplify the Rein-Murray theory of atolls; they certainly do not demonstrate its correctness.

In view of the slow accumulation and continual disintegration of organic sediments and of the increasing action of waves and currents upon them as their depth decreases, it is possible that the depth of submarine banks may be in some instances controlled through a rough balance between degradation by waves and currents as well as deepening by slow subsidence and aggradation by accumulating sediment. Whatever their origin, the accumulation of organic detritus will tend to build up the surface; and here be it noted that although aggradation by inwash of detritus from a drowned reef rim is less effective in large banks than in small ones, aggradation by precipitation of floating organisms and by accumulation of bottom organisms is not affected by area; for the larger the area the more numerous the organisms; a very large bank may therefore be built up about as fast as one of medium size. On coral reefs there are numerous agencies, from gnawing fish and grinding sea slugs to boring worms and adhering algae, which reduce coral rock to sand and silt of such fineness that it can be easily shifted by the waves and currents of the lagoons. If similar disintegrating

¹ T. Y. Buchanan, "On Oceanic Shoals Discovered by the SS. 'Dacia' . . . ," *Proc. Roy. Soc. Edinb.*, XIII (1886), 428-43. These banks and several others off the coast of Africa between the Canary Islands and Spain are shown on Hydrogr. Office chart 1743; they are all less than 10 miles in diameter; their depths vary from 23 to 96 fathoms.

² J. Murray, "Balfour Shoal, a Submarine Elevation in the Coral Sea," *Scot. Geogr. Mag.*, XIII (1897), 120-34.

agencies are at work on submarine banks, the fine detritus that they produce would be lifted from the shoal surface by the waves and currents and deposited on the steep exterior pitch; and the nearer the surface of the bank stood to the surface of the sea the more active would this process be.

Evidently, then, if a former atoll were transformed into a submarine bank with a depth of 60 or 70 fathoms at a time of active subsidence, it might be aggraded to a depth of 50 or 40 fathoms during a following time of still-stand; but further reduction of depth might be long prevented by wave work if no coral rim were built up around the margin of the bank. Hence, if still-stand periods are commonly of long duration and times of active subsidence are short-lived, a rough approach to similarity in the depth of banks would ordinarily prevail; banks of unusually great depth would occur only here and there for a relatively short period after active subsidence and would therefore be exceptional. In the case of submarine banks that have not subsided from a former existence as islands, but that have been built up by volcanic eruptions to such depths as 200 or 100 fathoms and have then stood still, a similar balance might be reached when their depth was reduced by organic aggradation to the critical level. As was previously noted, whatever truth there is in this supposition will militate against the acceptance of the Rein-Murray theory, which accounts for atolls by the progressive aggradation of still standing banks until they are brought to so small a depth that reef-building corals can be established upon them.

Need of oceanic exploration.—It seems improbable, however, that subsidence, if it be really so dominant an oceanic process as Darwin's theory implies, should not in some cases overcome aggradation and carry some banks down to such depths as 100 or 200 fathoms. The scarcity of large flat banks at such depths is manifestly a difficulty that the theory of reef upgrowth does not fully overcome. It is of course possible that further exploration of the ocean depths will discover additional examples and show that they are not so rare as they now seem to be; and inasmuch as there are unsounded areas in the Pacific as large as Australia, this possibility may be almost a probability; nevertheless, as long as

the facts are not more fully ascertained, the rarity of deep banks is, in my view, more unfavorable to Darwin's theory than any other objection that has been urged against it.

It may be noted that certain small sea-level reefs in Fiji appear to have been recently submerged by subsidence to a depth of 100 fathoms or more, after a previous appearance at sea-level and before their present emergence by elevation; they stand near the lofty atoll of Vatu Vará, which is now 1,030 feet above sea-level; at an earlier time, when the presumable foundation of Vatu Vará may have stood about as high as now so that a reef could begin to grow upon it, the small reefs also may have had their heads at sea-level; between then and now, when the reef of Vatu Vará was completing its upward growth upon its supposedly subsiding foundation, the small reefs must have been deeply submerged, because their small size prevented their continued upgrowth; I have suggested that they might then be called "extinguished," and that now, since they have been brought to the surface again by uplift, they might be called "resurgent."¹ It may be further noted that several lines of evidence, of which the latest one to be announced is found in an article by Foye,² indicate a recent eastward tilting in the eastern part of Fiji, and that some small submerged banks lie beyond the easternmost islands, as if the tilting in their district were too great to be overcome by upgrowth. Close-spaced soundings in that region would be of special interest. A tilting is also indicated to the northwest of Viti Levu, the largest Fiji island, as has been noted; there also additional soundings are desirable.

Extra-tropical submarine banks.—If prolonged crustal stability characterizes the intertropical oceanic areas in which volcanic foundations are crowned with atolls, it should also characterize extra-tropical oceanic areas where volcanic foundations are not reef crowned. Preglacial volcanic islands in these areas as well as atolls on the border of the coral zone, where the reefs must surely have been killed, should therefore be more or less completely reduced to submarine platforms of the same depth as the platforms that are supposed to underlie the submarine banks of the coral seas.

¹ "Extinguished and Resurgent Reefs," *Proc. Nat. Acad. Sci.*, II (1916), 466-71.

² "The Geology of the Lau Islands [Fiji]," *Amer. Jour. Sci.*, XLIII (1917), 343-50.

Large-scale ocean charts show that shallow platforms or banks do surround a number of extra-tropical volcanic islands, but the recorded depths do not correspond to the depths that abraded platforms must have, if they exist, beneath the great submarine banks of the coral seas. Just as the central depths of coral-crowned banks are the most significant measures there offered, so the central depths of extra-tropical banks—or the depths close around their residual, cliff-rimmed islands—are also the most significant, because in both cases these central depths give the nearest indication of the attitude of sea-level when abrasion was taking place. It is true that the central surface of abrasion may have been worn somewhat below sea-level and that it may have been since then somewhat aggraded; but as both these variations may have similar values in all cases, it remains true that the central depths are the most significant for our purposes. The following examples may be cited.

Two small volcanic islands, Bird and Necker, in the north-western extension of the Hawaiian group, have been described by Elschner¹ as rising with strongly cliff borders of resistant lavas from extensive banks, one or two score miles across. Bird Island, latitude 23° N., is 900 feet high; its bank has depths of from 12 to 20 fathoms near the island; Necker Island, latitude $23\frac{1}{2}^{\circ}$ N., has a height of 300 feet; its bank has depths of less than 10 fathoms for a quarter-mile from its cliffs. Both banks deepen to 40 or 50 fathoms at their borders. It is noteworthy that coral reefs occur not far away, and it is therefore eminently possible that reefs may have been formed on these island banks also, either in preglacial time or in an interglacial epoch, the latest of which was, according to glacialists, longer and warmer than the present postglacial epoch. But if this be the case, the presence of strong cliffs on the residual volcanic islands here makes the absence of spur-end cliffs on the reef-encircled islands of the torrid seas all the more significant.

In the South Pacific, Norfolk Island, a volcanic mass in latitude 29° S., between New Zealand and Australia, is strongly cliff,

¹ C. Elschner, "The Leeward Islands of the Hawaiian Group." Reprinted from the *Sunday Advertiser*, Honolulu, 1915.

according to Carne¹ and Laing.² Its cliffs rise 250 feet above sea-level and form a wall-like coast with few indentations; it surmounts a vast bank which is represented on British Admiralty charts 215 and 1110 as measuring 60 miles north and south by 20 miles in breadth, with depths of 20 fathoms near the island and of 40 or 50 fathoms near the margin. Similarly, Lord Howe Island, east of Australia, in latitude 32° S. (not to be confounded with a great atoll sometimes given the same name, but better known as "Ongtong Java," north of the Solomon group), presents, as described by Etheridge,³ a ragged and cliff margin on its convex northeastern side, and a coral reef inclosing a narrow lagoon on its concave southwestern side; it is shown on Admiralty chart 2014 to rise from a bank from 8 to 12 miles in diameter, submerged to depths of from 20 fathoms near the island to 40 fathoms near the bank margin. Not far away the gigantic volcanic stack, known as Balls Pyramid, with a height of 1,816 feet that exceeds its shorter diameter at sea-level, rises from a 3×7-mile bank, with cliff-base depths of 15 or 20 fathoms, and marginal depths of 40 or 50 fathoms. As in the case of Bird and Necker islands, these two southern examples may have been reef-encircled in preglacial or interglacial time, and may have suffered abrasion after the reefs were dead; but if so the reefs around the islands of the torrid sea cannot have been killed, for those islands are as a rule not cliff.

Mention may be made in this connection of certain exceptional intertropical islands that, like Tahiti and part of Hawaii, do possess cliff spur ends. Tutuila, the easternmost of the three larger Samoan Islands, is ancient enough to be more or less dissected, and yet modern enough to be still mountainous; it is well embayed, and some of the bays at least seem to be drowned erosional valleys and not merely unfilled spaces between adjacent volcanic masses; but on this significant though elementary point no sufficient evidence is available. According to Hydrographic chart 90, the salient

¹ J. E. Carne [Notes on Norfolk Island], *App. H., Ann. Rep. Dept. Mines N. S. W., for 1885* (Sydney, 1886), pp. 145-47.

² R. M. Laing, "Notes on the Chief Physiographic Features of Norfolk Island," *Trans. N. Z. Inst.*, XLV (1913), 323-26.

³ R. Etheridge, "The Physical and Geological Structure of Lord Howe Island," *Mem. Austral. Museum*, No. 2.

points of the island are rather strongly clift, and depths of 15 or 20 fathoms are shown close to the cliff base. Mayer has recently announced the occurrence of cliff-base benches 8 feet above present sea-level, and of a fringing reef that surmounts a submerged platform about 20 fathoms in depth; but he does not explicitly correlate the origin of the valleys, now drowned in embayments, and the headland cliffs, some of which are 500 feet high.¹ The Marquesas Islands, farther east in the Pacific and much nearer the equator than the many atolls in the neighboring Paumotu group, have no reefs, though fragments of coral are found in the bay-head beaches; their headlands are strongly clift, and the depths of from 12 to 20 fathoms are found a short distance offshore. Both of these examples strongly suggest that unprotected modern volcanic islands may have their spur ends clift by the ocean while valleys are eroded on their slopes; both suggest also that, as Dana suggested for the Marquesas and as Darwin pointed out in more general form, rapid subsidence may have drowned former reefs; if so, the subsidence must have been of so recent a date that no new reefs have yet been built up. These two island groups deserve abundant soundings on their banks and critical physiographic study of their shore lines.

If we assume for the moment that none of the islands here mentioned have subsided, several inferences may be drawn from the foregoing facts. The first is that the central depths of the extra-tropical banks, generally 20 fathoms or less, are decidedly smaller than the central depths of the large intertropical banks, which usually measure 40 fathoms or more; in both cases the banks may now be more or less aggraded, but no changes of depth thus brought about permit us to regard the present dissimilar depths as accordant and hence as confirmatory of abrasion at the same level by the lowered glacial ocean. Another inference is that of the two groups of banks it may well be the extra-tropical that are best ascribed to abrasion by the lowered ocean, because a lowering of sea-level by 20 or 25 fathoms, which would suffice to cut these banks, is in the opinion of some glacialists a more probable measure of the glacial lowering of the ocean than 40 or more fathoms, which is demanded for the cutting of the intertropical banks.

¹ A. G. Mayer, "Coral Reefs of Tutuila . . .," *Proc. Nat. Acad. Sci.*, III (1917), 522-26.

A third inference is that, as the extra-tropical cliff islands present no signs of a bench abraded in preglacial times at present sea-level, such a bench, if it ever existed, must have been completely destroyed by the undercutting of the present bench; to be sure, no bench would have been cut if the islands had been surrounded by reefs in preglacial time; but in either case we may further infer that if the ocean could accomplish so much abrasion on these hard-rock extra-tropical islands as is indicated by their broad platforms, cliffs ought to have been cut on the spur ends of the hard-rock inter-tropical islands; thus the conclusion stated in an earlier section is confirmed. A fourth inference is that, inasmuch as here again the marginal depths of the banks are about 40 fathoms, the recurrence of this measure indicates that the depths are not simply the work of abrasion by the lowered ocean, but of adjustment with respect to present sea-level between aggradation by inorganic and organic deposits and degradation by waves and currents. It is worth remembering in this connection that a number of soundings on the banks report "coral."

But the assumption that the islands here considered have not subsided is without support; the evidence given above that the island of Hawaii has suffered subrecent subsidence makes it not improbable that Bird and Necker islands also have subsided. In this case the fourth inference, just stated, would be of special importance; but the problem thus becomes so largely speculative that it need not be considered further at present.

Bearing of submarine banks on the coral-reef problem.—In summarizing the considerations thus far presented, let me state explicitly that I do not wish to insist that the recent subsidence of the Ceram Sea basin demonstrates recent subsidence in the China Sea, which lies 1,500 miles to the northwest; nor that the geologically modern movements in the Philippines and other Australasian islands absolutely demand contemporaneous movements in the foundations of the Tizard and Macclesfield banks 200 or 300 miles to the west of the Philippines; nor that subsidence of the foundations of these banks, if it should be proved, would fully certify to subsidence of the great banks in the Indian Ocean also; nor that the demonstrated subsidence of all these banks would unqualifiedly require the subsidence of all the atoll foundations in

the Pacific; nor that the argument based on the dissimilarity of central depths in intertropical and extra-tropical banks is necessarily fatal to the origin of the intertropical banks by the abrasion of still-standing preglacial islands. But, on the other hand, it does seem fair to urge that the abrasion of intertropical and extra-tropical banks can hardly have taken place (if it took place at all) at the same level, because of the present differences in their central depths; that the stability of the submarine banks in the China Sea, as postulated by the glacial-control theory, is made at least improbable by the instability of the neighboring islands and sea floors; and that, if the stability of these typical banks is improbable, then the stability of all the other banks and of atolls as well is rendered very uncertain; for if one smooth bank can be produced on an unstable foundation without the aid of abrasion, then the occurrence of smooth banks elsewhere and of smooth atoll-lagoon floors is no proof of stability.

Furthermore, it seems reasonable to question the value of the often-recurring depth of 40 fathoms at the margin of submarine banks and around coral-reef slopes as an indication of a former lowered level of the ocean, and to inquire, as above, whether it may not be an adjustment of aggraded surfaces to the present level of the ocean. In view of these various uncertainties on the one hand and open possibilities on the other, it is not an inherent strength, but an easily avoided weakness, of the glacial-control theory, especially when it is applied to such banks as those of the China Sea and hence presumably when applied to atolls in general, to maintain that no important vertical movements of the earth's crust are included in the processes by which atolls are produced. We may, indeed, in view of the reasons given on page 390 for discrediting the abrasion of atolls and low volcanic islands during the glacial period, and in view of the reasons later adduced against the long-continued stability in the China Sea, make special application of the results of this inquiry by saying that the Macclesfield bank cannot be safely regarded as representing a volcanic island, once as large as Hawaii, that has stood still long enough to be worn down to low relief and that was then planed off by the glacial ocean; it much more probably represents a large atoll, formed by upgrowth during the long-continued, slow subsidence of its foundation, and recently

drowned by a rapid submergence which the postglacial rise of ocean-level may have helped to produce.

Darwin's theory of the Pacific Ocean.—After Darwin had conceived the theory of subsidence and found that it accounted for the few reefs that he had himself seen as well as for many reefs seen by other explorers, he made further test of it by inquiring whether it would account for the distribution of reefs, and wrote on this aspect of the problem in his *Journal of Researches* on the "Beagle" (1840, pp. 566, 567) as follows:

When we consider the absence of both widely encircling [barrier] reefs and lagoon islands [atolls] in the several archipelagoes and wide areas, where there are proofs of elevation [in the form of "raised shells and corals, together with mere skirting (fringing) reefs"]; and on the other hand the converse case of the absence of such proof where reefs of those classes do occur; together with the juxtaposition of the different kinds produced by movements of the same order, and the symmetry of the whole, I think it will be difficult (even independently of the explanation it offers of the peculiar configuration of each class) to deny a great probability of this theory.

That candid statement contains the essence of a simple means of verification and serves to contradict those who later complained that Darwin had assumed that subsidence proved itself. He employed the same means of verification twenty years later in the *Origin of Species*, regarding which he wrote, "I believe in the doctrine of descent with modification, notwithstanding that this or that particular change of structure cannot be accounted for, because this doctrine groups together and explains . . . many general phenomena of nature." Unfortunately the two additional means of verification for the theory of intermittent subsidence as provided by embayed shore lines and unconformable contacts were not used by its author, but that aspect of the problem need not be further considered here.

The occurrence of fringes, barriers, and atolls was more fully discussed in Darwin's book on *The Structure and Distribution of Coral Reefs* (1842); here an appendix of 50 pages presents a summary of all records then available, the results of which were shown upon a map; and it was these results that led to certain generalizations as to broad areas of subsidence and of elevation in the Pacific which later observations have not confirmed. Darwin did not "venture to hope that the map is free from many errors," as he had to seek "information from all kinds of sources," but he trusted that

the map would "give an approximately correct view of the general distribution of coral reefs over the whole world" (123). He added: "We may therefore conceive that the proximity in the same areas of the two classes of reefs [barriers and atolls], which owe their origin to the subsidence of the earth's crust and their separation from those [fringing reefs] formed during its stationary or rising condition, holds good to the full extent which might have been anticipated by our theory" (125). Thus encouraged he constructed a theory regarding the movements of continents and ocean bottoms out of his theory of coral reefs: "The eastern and western boundaries of our map are continents, and they are rising areas: the central spaces of the great Indian and Pacific oceans are mostly subsiding; between them, north of Australia, lies the most broken land on the globe, and there the rising parts are surrounded and penetrated by areas of subsidence" (143).

The facts of reef distribution as now reported are much more complicated than they appeared to be in 1842. For example, Darwin knew the Fiji group only as containing sea-level barrier reefs and atolls, and therefore charted it as indicating simple subsidence. Dana also interpreted the Fiji group in this way. Since those earlier years many high-standing reefs have been found in Fiji, and certain observers thereupon completely reversed the previous opinion and regarded Fiji as an area of simple elevation and as therefore contradicting Darwin's theory. Closer study gives abundant evidence to show that Fiji is really an area of complicated oscillation, and that its reefs—those now uplifted as well as those still at sea-level—were formed during times of submergence, apparently the result of subsidence. The latest statement to this effect is an article by Foye, cited above, concerning the eastern part of Fiji.

In view of the interesting complications thus brought forward, it has been said that, while the irregular uplifts and subsidences in Fiji support Darwin's coral-reef theory, they "negative the idea of a general depression of the Pacific islands, a further conception of the theory." This seems to me unwarrantably to condemn the subsidence theory of coral reefs. The simple theory of the general subsidence of the Pacific Ocean bottom was based on a belief regarding the subsidence of many Pacific islands, and is not an essential part of the subsidence theory of coral reefs; the theory of the

Pacific was a supplementary idea which now proves to be erroneous because it was based on faulty or incomplete observations quoted by Darwin from the reports of other explorers.

Darwin's coral-reef theory itself simply postulates that reefs are formed by upgrowth, whenever and wherever fitting foundations in an ocean of proper temperature subside at a proper rate. This theory now needs subordinate modification by compounding the periodic changes of ocean-level during the glacial period with the changes due to subsidence and elevation; but the theory needs no change because Fiji is shown not to be an area of simple subsidence; indeed the theory is more strongly supported than ever, now that it is found to hold good, not only for areas of simple subsidence, but for an area of complicated oscillation such as Fiji proves to be.

It is only the over-simple supplementary theory regarding the Pacific that is negatived by the new observations; that theory must be replaced by a newer and more complicated theory of the Pacific, which may well include relatively local subsidence of active or recently active volcanoes, as intimated in an earlier section, as well as ocean-floor deformation of any kind, local or widespread, dependent or independent of volcanic action; but such a theory of the Pacific does not demand any modification whatever in the theory of reef upgrowth on slowly or intermittently subsiding foundations; for, as Darwin put it, "during a gradual subsidence the corals would be favorably circumstanced for building up their solid frameworks and reaching the surface, as island after island disappeared" (94), to whatever process the subsidence might be due. That elastic theory, with its various special adaptations to special conditions as stated by Darwin, and modified as need be by combining changes of ocean-level with subsidence of reef foundations, still seems to me to give a better explanation than any other for the various and complicated phenomena of coral reefs. Molengraaff's recent suggestion¹ that the subsidence, which determined the formation of most atolls, has resulted from the local and isostatic sinking of their volcanic foundations is an important contribution to the problem, which I have briefly considered elsewhere.²

¹ "The Coral Reef Problem and Isostasy," *Proc. k. Akad. Wet. Amsterdam*, XIX (1916), 610-27.

² "The Isostatic Subsidence of Volcanic Islands," *Proc. Nat. Acad. Sci.*, III (1917) 649-54.